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SCALING ANALYSIS OF THERMOGRAPHIC IMAGES USING NEURAL NETWORKS

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13. ABSTRACT (Maximum 200 words)

Sequences of thermographic images of burning residue produced by M198 155 (unicharge) test rounds fired at Yuma Proving Ground (YPG) were collected for analysis to elucidate the evolution of conditions in the breech after firing and to provide guidance in determining safe loading protocols for future autoloaders. In order to better understand the thermal environment in the breech, we are developing advanced analytical tools that can be used to quantitatively characterize sequences of thermographic images. However, for this study the calibration data required to extract the temperature profiles the YPG thermographic images for these analyses was unavailable. No analytic solution could be determined to perform the highly nonlinear reverse transformation from RGB space to intensities; therefore, a neural network was employed. Furthermore, the experimental data provided by YPG were only measurable over a restricted range of temperatures extending from approximately 80°C up to 110°C. Since the highest temperatures measured in the thermographic data did not correspond to a hazardous condition, more complex measures than simple statistical averages of the temperature had to be used. A new numerical technique represented by sparse data sets was introduced for measuring the scaling properties of single-valued surfaces in 3-space.

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INTRODUCTION

As the Army moves toward higher energy ammunition and faster rates of fire, there is a greater risk of premature ignition when reloading rounds. A burning residue signature study performed by the Olin Defense Systems Group (ref 1) has indicated that the burn duration of gun bore debris almost always far exceeds the interval between rounds envisioned for future tank autoloaders. Therefore, if the residue is neither completely burned during firing, nor evacuated before the breech is opened, then there exists a potential for a hazardous condition.

Sequences of thermographic images of burning residue produced by M198 155 (unicharge) test rounds fired at Yuma Proving Ground (YPG) have been collected for analysis to elucidate the evolution of conditions in the breech after firing and to provide guidance in determining safe loading protocols for future autoloaders. In order to achieve these objectives, we are defining quantitative measures of the state of the system based on the YPG experimental thermographic image sequences, and we are developing techniques to predict the time to reach a safe-to-load state given a sequence of prior quantitative results. Procedures are being developed along the following lines to better understand the thermal environment in the breech after firing:

1. Conventional analysis with system characterization provided in terms of:

    • Statistical distributions of thermal gradients and other quantitative measures of the temperature distribution in the breech
    • Statistical particulate-hot gas distributions

2. Fractal approaches with system characterization provided in terms of :

    • Fractal measures deduced from hot gas and particulate perimeter-area analysis with coastlines defined by constant temperature contours
    • Fractal measures deduced from the analysis of the local scaling of hypersurfaces formed in temperature-position space

The present report describes results obtained by the application of the latter fractal approach, which required the development of specialized local fractal analysis techniques and had potential for providing insight into the state of general complex heterogeneous systems. We anticipated that optimal characterization of the YPG thermographic image sequences would employ a combination of the approaches outlined above and possibly some others as well.

BACKGROUND

The temperature distributions characteristic of the burning residue in the breech after firing are heterogeneous with the hot regions in the images comprising a relatively small fraction of the imaged area as shown in Figure 1. Additionally, the hot particulate/gaseous regions are mobile and the spaces

between the hot particle/gas regions are contaminated by noise. In our study the experimental data were further limited by recorded temperatures extending only from approximately 80°C to 110°C. Since the highest temperatures measured in the thermographic data did not correspond to a hazardous condition, more complex measures than simple statistical averages of the temperature had to be employed. For example, we have analyzed the evolution of particle sizes and temperature gradients in regions having temperatures greater than a threshold value for a number of firing sequences. However, no trends have yet been identified.

A complementary approach focuses attention on the complexity of the temperature distribution as reflected in its local fractal scaling properties. In particular, the temperature distribution has to be characterized in terms of the local fractal dimension D. The techniques developed for the determination of the local fractal scaling and typical results obtained by application to YPG thermographic image sequences are described in this report.

NEURAL NETWORK TRANSFORMATION

In order to perform scaling analysis of the thermographic images, the intensity profiles of the thermographic images had to be extracted from the red-green-blue (RGB) representation. This is because the calibration data normally recorded with the thermographic images were unavailable. The calibration scale on the bottom of Figure 1 shows the gray scale intensities corresponding to temperature values within a specified range. It also shows the upper and lower saturation regions beyond which temperature data were not recorded. In the figure, temperatures below 80°C were not recorded as gray scale intensities, but instead as a combination of unequal RGB values. A different set of RGB values was used for temperatures exceeding 110°C. Since the data were extracted from a low-resolution video source, the actual RGB values are unknown. The video source also introduced two transition zones between the gray scale extremes and the saturation regions. The RGB values within these zones vary significantly. No analytic solution could be determined to extract the temperature profiles from the RGB data; therefore, a feedforward neural network was employed to perform the highly nonlinear reverse transformation. Excellent results were obtained using the three RGB values as a feature vector, thirty neurons in a single hidden layer, and a single output neuron corresponding to intensity. The network was trained on a single frame using a random selection of pixels (RGB values) in each of the saturation regions, the transition zones, and the gray scale calibration region. The network converged to a solution and successfully transformed each pixel in the frame from which the training data were extracted, as well as (typically 1000) subsequent frames in the firing sequence. Figure 2 shows the results of the neural network transformation of Figure 1. The transition zones and background noise have been removed. The same network was also successfully used in obtaining the temperature profiles for the remaining ten (independently-measured) firing sequences.

FRACTAL CHARACTERIZATION

The Fractal Hypersurface

A hypersurface is defined for the temperature distribution in a thermographic image by combining the $\{i,j\}$ integer spatial coordinates with the integer gray level coordinates (which correspond to temperature values) to form a set of points belonging to a hypersurface $g(i,j)$. In order to define such a surface, the number of gray levels must be selected to correspond to one $\{i,j\}$ pixel spacing. This metric should be selected to maximize the variations in the local D-values for the transition region between safe and unsafe to load. In practice, values near one gray level per pixel spacing yielded "satisfactory" variations in local D for the YPG data and no attempt has been made thus far to optimize the metric. The thermographic image hypersurfaces are extremely heterogeneous: regions corresponding to hot particles and/or hot gasses have relatively high local fractal dimensions, but correspond to a relatively small fraction of the volume. Regions between the hot particles and hot gasses, which comprise the major part of the volume, have local D-values near 2.0.

The Fractal Analysis Technique: Triangulation

In order to measure the local fractal dimensions in the heterogeneous YPG thermographic image sequences, a fractal analysis technique is required to measure local D values based upon limited sets of data. Such an analysis would be impossible employing standard techniques of fractal analysis. For example, correlation-integral or box-counting fractal analysis of fractal sets having D near 2.0 requires more than 10^5 points for convergence within 15 percent (refs 2,3). Note, $10^5 >> 17^2 = 289$. Therefore, a specialized technique of fractal analysis has been developed for the analysis of single-valued continuous surfaces of the sort described by $g(i,j)$.

The principle underlying the triangulation algorithm is that if the (i,j)-lattice is considered as the base plane of a set of hypercubes, then for a continuous single-valued surface, the sets of points

$$S(i,j) = \{(i,j,g(i,j)), (i+1,j,g(i+1,j)), (i,j+1,g(i,j+1)), (i+1,j+1,g(i+1,j+1))\} \tag{1}$$

determine that *all* the boxes located between the member of $S(i,j)$ having the largest value of g and the member of $S(i,j)$ having the smallest value of g contain pieces of the hypersurface. Furthermore, each point $(i,j,g(i,j))$ serves to (partially) define four $S(i,j)$, and therefore four sets of occupied boxes. The actual implementation of the triangulation principle focuses on the scaling of a hierarchy of approximate tessellation of the fractal surface based on the measured points $(i,j,g(i,j))$. The triangulation algorithm determines the fractal dimension of single-valued surfaces in 3-space. A detailed description of the triangulation algorithm, including a discussion concerning its sensitivity to uniformly and normally distributed random noise, is presented in Reference 4.

Consider L by L images, where L is taken as

$$L = 2^n + 1 \text{ for integer } n \qquad (2)$$

to facilitate triangular approximations. For such choices of L, sets of triangles may be defined that tessellate the surface with no gaps or overlaps, whose vertices coincide with subsets of points on the lattice, and whose projections in the (i,j)-plane are right triangles of side lengths $Y(m)$, which are given by

$$Y(m) = 2^m \text{ for } m = \{0,1,...n\} \qquad (3)$$

The small $Y(m)$ approximations to the fractal surfaces scale according to

$$\frac{d\, ln(A(m))}{d\, ln(Y(m))} \xrightarrow[m \to 0]{} 2 - D \qquad (4)$$

where $A(m)$ is an approximate surface area that can be expressed in terms of individual triangle areas

$$A(m) \equiv \sum A_i(m) \qquad (5)$$

for the triangulation based on $Y(m)$ by $Y(m)$ cells. Equation (3) defines the fractal dimension D. A slightly more general form of the triangulation algorithm, which allows for

$$Y(a,b,c,...) = 2^a\, 3^b\, 5^c... \text{ for } a = \{0,1,...n_1\},\ b = \{0,1,...n_2\},\ c = \{0,1,...n_3\},... \qquad (6)$$

is presented in Reference 4.

Figure 3 shows useful values of D that were based upon 17x17 patches of elevation data of the thermographic image of Figure 2. The values of the D contours in Figure 3 range from 2.0 to 2.5.

LAM IMPLEMENTATION

The triangulation algorithm is capable of reliably determining *fractal* scaling parameters of relatively sparse, heterogeneous data sets. However, the generation of local D-maps for each frame of a set of firing sequences is impractical without exploiting the inherent parallelism of the problem. A suite of homogenous parallel procedures has been developed to map the triangulation algorithm to a multicomputer platform using a subset of Trollius (Ohio State University and Cornell Research Foundation) called *LAM* (ref 5) for interprocess communication. *LAM* supports only general purpose UNIX machines connected via a local area network or the Internet. *LAM* is a node-oriented computing environment that uses an identifier assigned to each node (nodeid) as the primary synchronization for communication. The nodes are usually fully connected (maximum 1-hop distance) since the network is

4

generally a shared resource. In our parallel implementation of the triangulation algorithm, a master process assigns equal-sized regions of each thermographic image to slave processing nodes for computation of local D-map subsets. The processing nodes return the results to the master process, where the D-map is assembled and the slave processors are assigned new regions to analyze. Although this approach does not fully exploit the communication advantages of a fully connected network, the load balancing has resulted in a performance improvement directly proportional to the number of workstations. This is likely due to the high computation/communication ratio and the relatively small number of workstations comprising our multicomputer.

The results shown in Figure 3 are limited because of the restricted distribution of recorded temperature values. Meaningful values of D can only be obtained where the complexity of the temperature distributions is faithfully represented in at least a 9x9 region. These regions are usually limited to small areas bounding the perimeter of larger particles. The D-maps were computed for each of the neural network transformed images in all of the firing sequences. The results are being included with conventional statistical measures (thermal gradients, temperature distributions, etc.) to help develop a database for a safe-to-load sensor design.

SUMMARY

A better understanding of the thermal environment in the breech after firing will enable engineers to provide guidance in determining safe loading protocols for future autoloaders. Quantitative characterization of complexity in the temperature distribution of thermographic data complements conventional statistical analysis techniques and provides additional insight into the nature of the problem. The use of standard analysis techniques to extract the scaling parameters of the thermographic data would yield inaccurate results because of the limited size of the data sets. Therefore, the triangulation fractal analysis technique was developed to provide a means of measuring local scaling properties of sparse data.

The recorded RGB values comprise a highly nonlinear representation of the actual temperatures. No analytic inverse transformation could be determined; therefore, a neural network was employed for extracting temperature intensity profiles. The computation of local D-maps for sequences of thermographic images using triangulation is numerically expensive, so the algorithm has been mapped to a powerful message-passing multicomputer using the *LAM* programming environment for interprocess communication. Several thermographic image sequences collected at YPG have been analyzed using triangulation and conventional analytic approaches in order to characterize the state of the system. The results are being used by our development engineers to help establish a database for a safe-to-load sensor design.

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Fig. 1: Thermographic Image
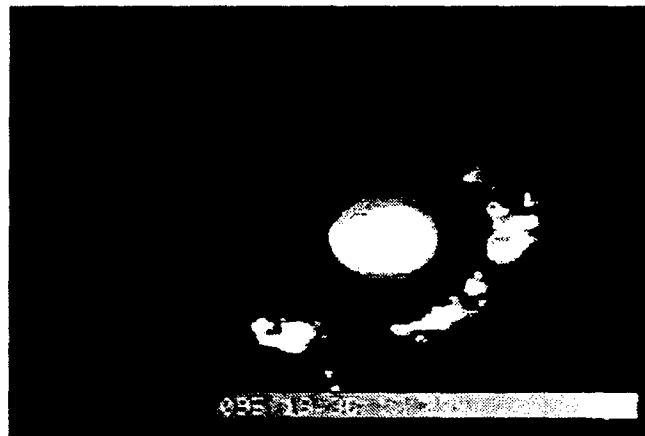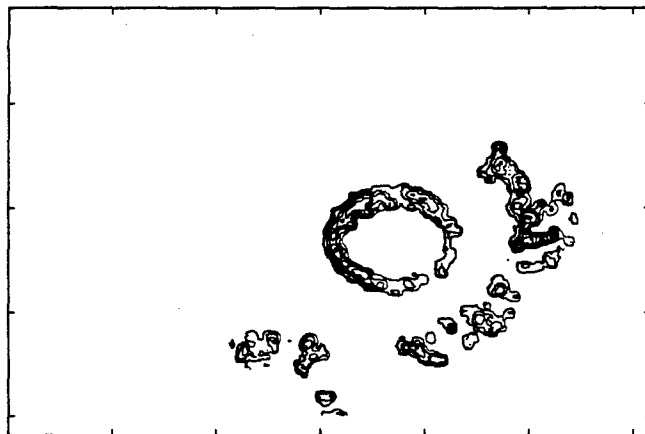

Fig. 2: Neural Net Transform

Fig. 3: D Contours

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